Designing for circularity: exploring configurator-based decision support for Eco-design in food packaging[*]

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Abstract

The packaging industry occupies a central position in the sustainability transition, particularly as regulatory frameworks increasingly mandate alignment with circular economy (CE) principles. In the European Union, the upcoming Packaging and Packaging Waste Regulation (PPWR), effective from January 2025, requires all packaging to be either reusable or recyclable in a technically and economically feasible manner. Since the majority of a product's environmental burden is determined during its early design phase, digital tools must evolve beyond conventional parametric modeling to incorporate environmental metrics, material recovery pathways, and lifecycle intelligence. While sustainable packaging design has received growing academic attention, the deployment of AI-based configurators to support eco-design and end-of-life strategies remains underdeveloped. This study investigates the potential of product configurators as intelligent, rule- based decision-support systems capable of embedding CE-aligned design logic in the food packaging sector. Adopting a multi-method empirical approach, combining Multi-Criteria Decision Analysis, Analytical Hierarchy Process, and expert evaluation, the research assesses the relative suitability of reuse, mechanical recycling, chemical recycling, and organic recycling against criteria defined by industry specialists. Furthermore, the study develops a conceptual framework for a next-generation configurator, designed to integrate eco-design principles, modular product architecture, and traceability data within packaging systems. Findings indicate that configurators can be re-engineered to function as intelligent interfaces for operationalizing CE principles in product development workflows. The study highlights modularity, material knowledge, and traceability as critical enablers, providing a roadmap for engineers and practitioners developing CE-compliant packaging configurators.

Keywords

eco-design, configuration systems, sustainable packaging, circular economy, end-of-life strategies, lifecycle-based design [1]

1. Introduction

Packaging has become a critical target for systemic redesign in the transition toward resource-efficient and sustainable production systems. Its ubiquity in consumer markets and its significant contribution to post-consumer waste make it a key intervention point for circular economy (CE) strategies [1]. As environmental concerns intensify and natural resource constraints become more pronounced, both regulatory institutions and industrial actors are seeking to replace linear, single-use models with systems oriented toward reuse, material recovery, and lifecycle closure. In this context, the forthcoming European Packaging and Packaging Waste Regulation (PPWR), entering into force in 2025, introduces mandatory requirements for all packaging placed on the market to be either reusable or recyclable in a technically and economically viable manner [2].

The implementation of CE principles in packaging design necessitates a shift not only in material selection and manufacturing methods but also in the digital systems that support design decision-making. While the academic literature on sustainable packaging has matured considerably, current industrial design tools remain largely focused on performance, branding, and

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cost metrics, often omitting environmental or end-of-life considerations. As a result, the opportunity to embed lifecycle intelligence and regulatory compliance directly into the design phase remains underexploited.

Digital product configurators, originally developed for managing product variability and enabling mass customization, offer architectural features that could be adapted to meet these new sustainability requirements. These systems are structured around constraint propagation, rule-based validation, and user-guided decision paths, enabling them to integrate environmental data, simulate product usage scenarios, and support design-for-recyclability or reuse [3-4]. However, the vast majority of current configurator applications in the packaging domain are limited to superficial customization of graphics, size, or labeling, and do not address eco-design functions such as modularity, material traceability, or End-of-life (EoL) strategy optimization.

The present study explores the extent to which configurators can be programmed to act as intelligent design systems for CE-aligned packaging. Specifically, the research aims are to (a) identify the most critical sustainability criteria as perceived by packaging professionals, (b) assess the relative performance of key EoL strategies across those criteria, and (c) define the structural and functional requirements for configurators capable of supporting CE-compliant product development. To address these objectives, a two-phase empirical methodology is employed. The first phase applies Multi-Criteria Decision Analysis (MCDA) and the Analytical Hierarchy Process (AHP) to evaluate expert preferences for four EoL pathways: reuse, mechanical recycling, chemical recycling, and organic recycling. The second phase proposes a conceptual framework for configurator functionality based on empirical findings and the evaluation of an existing digital configurator platform used in the food packaging industry.

The implication of the present study aims at contributing both at theoretical and managerial levels. On a theoretical level, it aims to advance the understanding of how design configurators can be aligned with circular economy imperatives. Managerially, it aims to identify the technical enablers, modularity, traceability, and material intelligence that could inform the development of next- generation configurators capable of meeting circular design principles and sustainability demands.

2. Theoretical background

2.1. Circular packaging: opportunities and challenges

Packaging plays an important role in the circular economy. To reduce its environmental impact, it is necessary to review its production processes, materials, and especially its End-of-life [5]. In the circular economy model, the revision to a sustainable perspective should be done at the initial design stage in which the decisions about materials and their reuse or End-of-life can be made.

In the product design phase, products are developed to be reused or returned to the environment in a way that benefits ecosystems and eliminates waste [6]. An eco-design perspective assesses the environmental impact of a product throughout its life cycle. According to the principles of circular and waste management [7], there are five possible actions to decrease the pollution that packaging creates: I) reject the use of packaging, II) rethink the concept of packaging to achieve a more sustainable option, III) reduce the use of material and energy used to produce packaging, IV) reuse packaging, and V) recycle packaging materials.

Circular economy (CE) models focus on reducing waste and extending the life of products through recycling, reuse, and remanufacturing practices [2]. A business model describes business operations, and the values connected and how the organization achieves them. It is important to define precisely how values are achieved in closed material chains [8]. The application of circular business models requires interventions in design, production, optimal product utilization, waste reduction, product life extension, and increased resource efficiency [9]. On the other hand, in traditional supply chains, for example in food, production processes typically follow a linear model, where products are created, consumed, and ultimately discarded at the end of their life cycle. In this scenario, packaging is often viewed merely as a means to protect and transport the product, representing the endpoint of its lifecycle. However, in the context of CE, packaging is recognized as a valuable product rather than viewing packaging solely as the end of processing or waste. In other words, within the CE framework, packaging consists as an integral component of the product life cycle. Moreover, the end- of-life phase includes the design of packaging, promoting practices such as reuse, recycling, and recovery, thereby extending its value and reducing overall waste. Consequently, the transition from a linear to a circular economy not only redefines the role of packaging but also enhances sustainability. For instance, the application of CE principles within food supply chains is significantly improving sustainability and resource efficiency, especially toward packaging. Many companies are adopting bio-degradable and compostable packaging, reducing environmental impact and reliance on fossil fuels. This fosters a more sustainable approach aligned with CE, contributing to environmental preservation and sustainable consumption. The deposit return system (DRS) is an example of reuse in packaging where a selective collection system mainly used for single-use beverage packaging. It works by charging the consumer a small refundable deposit, in addition to the purchase price of the product. This deposit is fully refunded when the consumer returns the empty packaging—such as bottles or cans—to a designated collection point, often available at retailers. This encourages consumers to return the packaging, helping to increase recycling rates substantially. This model is primarily used for materials like glass, plastic (notably PET), and aluminum containers for beverages.

Brands like Coca-Cola and Unilever use recycled materials, closing the loop on waste. Innovative solutions like edible packaging and reusable packaging systems are also emerging, further minimizing waste and optimizing material life cycles in food packaging [10]. In this context, biodegradable materials are often highlighted for their ability to decompose naturally, thus reducing waste and environmental impact. Biodegradable packaging refers to materials that can break down into natural substances, such as carbon dioxide, water, and biomass, through the action of microorganisms within a specified period of time. Examples of biodegradable packaging include plant-based plastics made from renewable resources like starch and polylactic acid (PLA), as well as traditional materials such as paper and organic fibers. These materials decompose through natural processes, making them more environmentally friendly compared to conventional petroleum-based plastics. The use of biodegradable packaging contributes to a closed- loop system by redirecting waste away from landfills, where it would otherwise contribute to methane emissions under anaerobic conditions. Instead, when disposed of in composting facilities or through home composting, biodegradable packaging can be converted into valuable compost, enriching soil and supporting plant growth while minimizing the overall carbon footprint associated with packaging waste [11]. This means that while biodegradable options are valuable, they should be part of a strategy that includes innovative recycling processes and efficient resource management to achieve true sustainability in packaging solutions [12]. Whether biodegradable packaging can play a crucial role in reducing landfill waste, it is essential to ensure that these materials are integrated into a broader system that prioritizes circularity. For instance, some biodegradable plastics may not fully degrade in home composting conditions, which typically operate at lower temperatures. For that reason, CE maximizes packaging material lifespan and minimizes virgin resource extraction through reuse, recycling, and recovery, going beyond simple biodegradability.

A specific role within the discussion of renewable materials and their lifecycle impacts is played by compostable materials. In packaging, these materials, which can be produced from biomass such as starch, cellulose, or renewable polymers, are intended to substitute for non-biodegradable plastics. They are specifically designed to biodegrade in a composting environment, turning into carbon dioxide, water, and biomass within a certain time frame without releasing toxins and for contributing to a sustainable nutrient cycle. They must meet specific standards (e.g., ASTM D6400 or EN 13432) that ensure they break down quickly and do not leave harmful residues. They must be also suitable for biological waste treatment through industrial or home composting systems. In brief, the use of compostable packaging is increasing due to the demand for eco-friendly solutions, promoting waste reduction and circular economy practices. However, certification and adequate composting infrastructure are essential for proper management of compostable waste [13]. Lastly, recyclable packaging refers to materials that can be processed and reused to create new products after their initial use, rather than being disposed of as waste. This type of packaging is designed in a way that allows it to be collected, sorted, and processed into raw materials for manufacturing new items. The recyclability of packaging depends on various factors including the material type, the presence of contaminants, and the local recycling facilities available to handle those materials [14]. Particularly, recycled materials come from post-consumer waste that has been processed and re-manufactured into new products. The recycling process helps reduce the demand for virgin resources and can mitigate environmental impacts compared to producing new materials from raw inputs. However, the recycling rates for many types of plastics remain low due to contamination and the complexity of different polymer types.

While compostable and biodegradable materials offer alternatives to traditional plastics by providing options for waste treatment, recycled materials contribute to sustainability by reusing existing materials. Each type has its own advantages and challenges, and the choice often depends on specific application requirements and waste management systems in place. Accordingly, companies face the challenge in designing effective Reverse Logistics (RL) systems, crucial for transitioning to a circular economy.

Although the literature has produced a variety of digital methodologies and decision-support tools to address CE principles, particularly in the domain of end-of-life management, there remains a gap in the integration of these principles within the early-stage design processes for packaging systems. A notable contribution in this regard is the Reverse Logistics Support Tool (RLST), recently proposed by Mallick et al. [15], which assists firms in evaluating strategic motivations, contextual product characteristics, regulatory conditions, and system design variables to comply with CE principles. The RLST framework puts key CE considerations into practice by incorporating variables such as stakeholder engagement, digital technologies, and consumer behavior. Although RLTS provides substantial guidance for downstream operations, particularly the recovery, sorting, and treatment of post-consumer packaging, its functionality in guiding upstream decision-making remains limited. Specifically, the RLST tool do not embed lifecycle-aware intelligence into the design phase, where up to 80% of a product's environmental footprint is determined [8]. Furthermore, they lack the capacity to support modular design thinking, traceability integration, and user co-design all of which are increasingly recognized as core enablers of circularity in packaging [7]. In this context, there is a critical need for digital tools implemented with systems that bridge CE- compliant logic directly into product development workflows. The present paper conceptualize that such systems could be extended beyond conventional rule-based configurators used in mass customization, evolving into intelligent, interactive platforms that simulate EoL pathways, assess regulatory compatibility, and support sustainable material selection at the point of packaging design to align design processes with environmental compliance requirements, consumer expectations, and circular material flows from inception.

2.2. Digital Configurators for Circular Co-Design

In the context of sustainable innovation and circular economy (CE), the implementation of digital configurators has emerged as a critical enabler for integrating co-design methodologies, stakeholder engagement, and consumer-centered innovation. Prior research has demonstrated that sustainability goals are more effectively achieved through multi-actor collaboration, particularly when stakeholders contribute distinct competencies and sectoral perspectives to a shared design process [16-17]. Digital tools serve not only as technological platforms but also as relational infrastructures that support resource-sharing, joint knowledge production, and circular-oriented innovation.

In this regard, consumer participation plays a crucial role, not only during the consumption phase but throughout the entire product lifecycle. The acceptance and active involvement of consumers are prerequisites for extending product longevity and maximizing material circularity [18]. Indeed, consumer co-design contributes to aligning product functionality with user values, facilitating behavioral change, and ultimately enhancing sustainability outcomes. Previous research has increasingly focused on how consumer perceptions of circularity influence both purchase and disposal behavior, highlighting the urgency of integrating behavioral science into lifecycle assessments [19].

Mass customization (MC), as a production paradigm, provides a powerful mechanism for aligning individual consumer needs with scalable and sustainable production systems. When embedded within a CE framework, MC enables firms, particularly SMEs, to reduce material waste, enhance resource efficiency, and stimulate demand for eco-designed products [20]. The process of co- innovation, whereby customers and producers co-create value, is significantly amplified by digital configurators that facilitate real-time feedback loops and participatory design choices [21-22].

Online Sales Configurators (OSCs), in particular, represent a mature instantiation of this model. They function as knowledge-intensive systems designed to support product development, delivery, and personalization [23-24]. OSCs reduce cognitive load during the decision-making process by guiding users through structured choice navigation paths, thereby minimizing complexity while preserving design freedom. By managing constraints, validating configurations, and simulating outcomes, these systems create highly engaging user experiences that are simultaneously efficient and satisfying [25- 26].

Specifically, when OSCs would be designed to support sustainable product attributes, they could significantly increase customer willingness to pay a premium for customized products [27]. This effect is amplified when configurators enable users to understand and visualize the environmental value embedded in their design decisions, fostering both individual agency and systemic alignment with circularity goals. Recent studies have confirmed that rewarding customization experiences not only increase perceived product value but also positively influence repurchase intentions and long-term brand loyalty [28]. In addition to enhancing user experience, configurators have demonstrated operational benefits for manufacturers. These include shorter lead times, reduction in design errors, improved product–market fit, and lower material consumption. From a system engineering perspective, configurators contribute to the optimization of product architectures and supply chain coordination, particularly in modular and variant rich environments [29-30]. When integrated with circular metrics, such as lifecycle data, recyclability indexes, and traceability modules, configurators evolve into adaptive platforms capable of orchestrating design choices that comply with environmental regulations and sustainability standards.

3. Methodology

The research design of the present study is structured on a multi-phase empirical research design. To address research aims (a) and (b), the investigation employs a combined Multi-Criteria Decision Analysis (MCDA) and Analytical Hierarchy Process (AHP) framework. Grounded on previous research [31-32] the adopted approach enables a quantitative evaluation of the relative importance of sustainability criteria and preferences for different EoL strategies by industry experts. Specifically, MCDA provides a prioritization of design criteria in terms of environmental, economic, social, and technical relevance, while AHP [33] facilitates the pairwise comparison of EoL alternatives, specifically reuse, mechanical recycling, chemical recycling, and organic recycling, against those criteria. To address the research objective (c) , the study proposes a conceptual framework for the development of a CE-compliant product configurator. The framework is grounded in existing literature on circular product design, eco-design regulation, and digital configuration systems, and is empirically informed by a test on a real case study analysis of Packstyle, a company operating in the food packaging sector. Packstyle (the real name) is a SME (Small Medium Enterprise) expert in online mass customization (Web-to-print). The idea came from the request to have customized flexible packaging for small runs. In this sector, the traditional machines have high operating costs and work only on large orders of food brands or manufacturers. Packstyle was created to satisfy a new niche market, that of small businesses that need packaging for their products but demand limited runs and in a very short time. The driving force came from the innovation culture of the company and the availability of one of its largest suppliers who had a machine to do experimentation on digital printing in flexible materials. The case is used to identify limitations in current customization platforms and to derive functional requirements for a next-generation configurator designed to align with CE principles.

As the packaging industry transitions toward compliance with upcoming EU directives such as the Packaging and Packaging Waste Regulation (PPWR) [2], the role of configurators is set to expand beyond customization. Their potential lies in supporting modular, traceable, and regulation- compliant packaging systems, thereby aligning technological innovation with circular economy imperatives. By embedding sustainability constraints and consumer-driven logic into digital design workflows, configurators can bridge the gap between technical feasibility and behavioral adoption, paving the way for more resilient and circular production ecosystems.

3.1. Multicriteria Decision Analysis

The MCDA is a decision-making method crucial when multiple criteria has to be considered since it enables a better valorization of multiple points of views (e.g. from stakeholders, experts, respondents) [33]. For the purpose of this study, we present the pre-test phase of the MCDA and AHP methodologies. This testing stage is preparatory, serving to refine the methodological design and validate it for subsequent development. As detailed in Table 1, this phase involved a sample of experts from the packaging sector holding high specialized expertise and professional roles.

On an initial step the industry expert was asked to perform the Multi Criteria Decision Analysis Which consist of an iterative pairwise comparison of 10 criteria on Eco-design sustainability (e.g. C1 versus C2 versus C3). The resulting matrix provides the average of experts' evaluations which identify a classification of the 10 criteria from the most relevant to the least one in terms of Eco-design for packaging and EOL strategies. A second step of the MCDA is experts' evaluation of the four alternatives of EoL strategies, namely: reuse, mechanical recycling, chemical recycling and organic recycling, to evaluate the preferred end-of-life strategies to be implemented by the company in responding to Eco design and circular regulatory requirements. The alternatives of EoL strategies are evaluated by the industry expert on a 10-point value scale as an extension of the Likert scale (1 to 5) to provide a more completed industry centered perspective. The testing of the research design is performed by an expert from Packstyle with high specialized knowledge, experience and high-level responsible role in the packaging industry. The multilevel knowhow of the expert enables a unique opportunity to test the robustness of the empirical research design of the present study. While the MCDA step aims at identifying the sustainability criteria relevant for Eco design in the food packaging industry, the second step of AHP completed the scenario with the strategic perspective on EoL strategy.

Table 1
Experts' profiles

Expert	Role	Core Specialization	Key Sector
Expert id_NG	CEO, Packstyle	Business Strategy & Regulatory Compliance	Flexible Packaging (Food/Cosmetics)
Expert id_LG	Head of R&D, Plastigraf Trevigiana	Materials Engineering	Luxury & Cellulose-based Packaging
Expert id_SD	Researcher & Professor	Food Science & Eco-design	Academic Research & Food Innovation
Expert id_MS	Polymer Scientist	Macromolecular Science	Advanced Manufacturing (Aerospace/Medical)

3.2. Selection of the criteria and alternatives

For the purpose of the present study 10 criteria (C1-C10) were selected to include the sustainability dimensions of packaging. Grounded on previous study [31-32, 34]. Criteria were selected to represent the sustainability in terms of technological, environmental, social economic and transferal dimensions of sustainability, Table 2 reports a synthesis of the 10 criteria described in the following.

C1 Green production process refers to the adoption of technologies and machinery that allow for waste reduction, consumption reduction and productivity increase with the same resources. *C2 Durability* refers to the increase in the life cycle of the product (packaging). *C3 Green practices for End-of-life (EOL):* refers to the reuse of packaging materials in new products, the use of packaging multiple times for the same or different purposes and the biological decomposition of organic packaging materials (e.g. bioplastics and paper) into compost. *C4 Modularity* refers to the possibility of designing packaging with standardized elements that can be combined with each other in order to optimize space, resources and functionality along the entire supply chain (production, logistics, display and disposal). *C5 Eco-label reputation* (how a company is perceived with respect to its environmental commitment and sustainability). *C6 Social sustainability:* refers to how an organization, company or community promotes equity, well-being, human rights and social cohesion in the present and for future generations. *C7 Green Premium Price* refers to the additional price that the buyer (company/end consumer) is willing to pay for a sustainable product or service compared to a traditional, less environmentally friendly one. *C8 Green logistics optimization* refers to the set of strategies and solutions to optimize logistics (transport, storage, distribution) in order to reduce the environmental impact along the entire supply chain. *C9 Material knowledge* refers to the knowledge of innovative and sustainable materials. *C10 Traceability* refers to the importance of detecting, recording and tracking all information related to the path and history of the packaging.

Table 2
Synthesis of the criteria

Dimension	Criterion ID	Criterion Label
Technological	C1	Green production process
Technological	C2	Durability
Environmental	C3	Green practice for EoL
Environmental	C4	Modularity
Social	C5	Green brand reputation
Social	C6	Social sustainability
Economic	C7	Green premium
Economic	C8	Green logistic optimization
Transversals	C9	Materials Knowledge
Transversal	C10	Traceability

The alternatives of EOL strategies are identified in accordance with previous research [34] with the Packaging and Packaging Waste Regulation (PPWR) and the scope of the present study. Specifically, reuse refers to the EoL practices that enable the reuse of the packaging. Recycling is considered in both its options of mechanical and chemical processes of packaging breaking down.

Table 3 provides a summary of EoL practices.

Table 3
Alternatives of End-of life strategies

ID	EOL strategies	Description
A1	Reuse	Upcycling
A2	Mechanical Recycling	To mechanically break down of packaging
A3	Chemical Recycling	To chemically break down packaging
A4	Organic Recycling	Compostable packaging

To evaluate the quality of the answers provided by the expert, answers are evaluated using a "consistency ratio" indicator which measures the consistency within the set of answers of each expert. As its name says, the "consistency ratio" indicates whether the evaluations provided by a respondent are consistent with the entire set of his/her answers. The maximum threshold of the consistency value is 0.10. If the value is 0.10, the evaluation provided by the responded result is inconsistent and not valid. AHP step. Ten-point scale, as an extension of the Likert scale (1 to 5) is adopted to provide a more completed scenario of expert's evaluation on the EoL alternatives.

4. Results

In the MCDA phase, expert responses were evaluated using a consistency ratio threshold of 0.10 to ensure internal coherence. Criteria exceeding this threshold were excluded from the analysis. The evaluation of ten sustainability criteria revealed three dimensions with the highest average weights: modularity (0.30), materials knowledge (0.22), and traceability (0.15) (Tab. 3). These dimensions are considered, by the expert, as fundamental to the development of CE-aligned packaging configurations. Modularity was recognized for its role in enabling design-for-reuse and disassembly. Materials knowledge was highlighted as critical to determining recyclability, contamination risk, and material compatibility. Traceability was identified as a cross-functional enabler that supports regulatory compliance and facilitates transparent material flows (Table 4)

Table 4
Relevance of Criteria for sustainable Eco-design in food packaging

Dimensions	ID	Criterion Label		Score per dimension
Technological	C1	Green production process	0.06	0.17
	C2	Durability	0.11	
Environmental	C3	Green practice for EoL	0.27	0.30
	C4	Modularity	0.03	
Social	C5	Green Brand reputation	0.02	0.06
	C6	Social sustainability	0.04	
Economic	C7	Green premium	0.02	0.10
	C8	Green logistic optimization	0.09	
Transversals	C9	Materials Knowledge	0.22	0.37
	C10	Traceability	0.15	

After identifying the criteria with the highest and lowest weights for measuring end-of-life (EOL) performance, the empirical analysis proceeds by analyzing the values assigned by the company to the proposed alternatives of EoL namely: reuse, mechanical (MEC), chemical (CHEM) and organic (ORGC) recycling (Table 5).

From the AHP analysis of EOL strategies, all four pathways—reuse, mechanical recycling, chemical recycling, and organic recycling—received nearly equivalent aggregate scores (ranging from 55 to 57 out of 100). However, a more granular interpretation reveals a differentiated profile for each alternative.

Chemical recycling, although technologically complex and economically burdensome, scored highest in traceability (score: 10) and modularity (score: 10), indicating that its potential lies in managing heterogeneous material streams with high fidelity. Conversely, reuse strategies were most positively evaluated in terms of social sustainability (score: 8) and green premium acceptance (score: 9), illustrating their alignment with consumer values and market positioning. Remarkably, organic recycling, though often lauded for its biodegradability, performed poorly in terms of materials knowledge (score: 2) and traceability (score: 9), raising concerns about its compatibility with current data systems and compositional verification methods. Mechanical recycling, widely considered the most mature EOL solution, scored well across green logistics, green production, and durability but was not dominant in any single criterion.

Table 5
Relevance of EoL strategy in food packaging

		End-of-life alternatives	**Recycling**		
Criteria	ID	Reuse (A1)	MEC (A2)	CHEM (A3)	ORGC (A4)
Green production process	C1	5	7	5	7
Durability	C2	2	6	9	10
Green practice for EoL	C3	1	1	1	1
Modularity	C4	6	4	10	5
Green Brand reputation	C5	10	10	7	8
Social sustainability	C6	8	8	6	6
Green premium	C7	9	9	4	3
Green logistic optimization	C8	7	5	3	4
Materials Knowledge	C9	3	2	2	2
Traceability	C10	4	3	10	9
Tot		55	55	57	55

Taken together, these findings substantiate a multi-dimensional view of circularity where no single EOL strategy is inherently superior. Rather, the configurator must operate as a decision-support system capable of matching design choices to context-sensitive sustainability parameters.

5. Discussion

The empirical results of this study provide preliminary insights into how digital configurators may function as strategic enablers for the circular transition for a company operating in food packaging. The double evaluation steps, based on Multi-Criteria Decision Analysis (MCDA) and the Analytical Hierarchy Process (AHP), yields a structured classification of sustainability criteria and end-of-life (EOL) preferences grounded on company perspective from a specialized industrial stakeholder (Packstyle). Based on the achieved results, this section outlines a conceptual extension of the Packstyle online customization system into a next-generation digital product configurator designed specifically for Eco-design requirements and circular (CE) compliance. The conceptual framework is provided by merging results from expert evaluation with the current state of the art of Packstyle packaging configurator.

5.1. Regulatory framework and gaps in food packaging configurators

Currently, Packstyle offers customizable flexible packaging through its online platform, enabling users to configure the visual identity, dimensions, and accessory options of pouches such as doypacks, flat pouches, and pillow bags. However, the existing system is oriented primarily toward graphical personalization and format selection, without integrated support for environmental criteria, end-of- life (EOL) strategies, or sustainability logic. Packstyle configurator it is still needed to be programmed accordingly to implement those features necessary for aligning with the European Union's regulatory framework on sustainable packaging design. Particularly, within the context of the upcoming Packaging and Packaging Waste Regulation (PPWR) [2] and the Food Contact Materials (FCM) Regulation (EU) No. 10/2011. These normative instruments require that packaging be designed for recyclability, traceability, and food safety across the entire lifecycle, including end-of-life (EOL) processing. Accordingly, several functional and structural gaps can be identified in the present system.

First, the platform does not currently integrate material traceability logic. Traceability is not only a prerequisite for compliance with Regulation (EU) No. 1935/2004, on materials and articles intended to come into contact with food, but also a strategic enabler of circularity. For Packstyle to align with both the FCM framework and forthcoming digital product passport (DPP) mandates under the EU Green Deal, each configured pouch should be linked to a unique identifier that includes information about the base polymer, barrier layers, adhesives, inks, and functional additives. This would also ensure compatibility with audits by food safety authorities and recyclers, particularly where multilayer or metallized materials are involved.

Second, the current system of tools lacks eco-design integration [15], (i.e., real-time feedback mechanisms that inform the user about the recyclability class, reuse potential, or contamination risk of the selected configuration). This omission prevents designers and users from evaluating whether their pouch aligns with Article 6 of the proposed PPWR, which requires packaging to be "designed for recycling" according to harmonized criteria. Incorporating an LCA-based scoring mechanism or recyclability simulation module, based on CEPI or RecyClass guidelines would allow the configurator to dynamically assess whether a given pouch meets threshold recyclability requirements (e.g., >90% mono-material by mass).

Another major gap to be addressed is the absence of modularity assessment, which is essential to enable reuse or material separation in post-consumption phases. Although Packstyle provides accessory options like spouts, valves, and zippers, the configurator does not indicate whether these additions impact recyclability, nor does it recommend alternative combinations that would facilitate disassembly or reuse. To support circular design principles, the system should incorporate disassembly scoring and suggest configurations where pouch and closure are made from the same polymer family, in line with CEN/TC 261/SC 4 standards for material compatibility.

5.2. Conceptualizing a next generation of circular food pouch configurator

Although Packstyle already offers a robust customization platform, transforming it into a CE-compliant and regulation-ready configurator requires embedding traceability, disassembly planning, EOL simulation, and food safety compliance directly into the design logic. Such an extension would not only ensure alignment with EU directives and Italian consortia (e.g., CONAI, COREPLA), but also position Packstyle at the forefront of digital eco-design innovation in flexible packaging.

To coherently implement these improvements, Packstyle's configurator (in advance for shortness: *P Configurator*) should evolve into a multi-layered digital decision-support system, where regulatory logic, material specification, and design modularity converge. Technically, this may involve integration with LCA platforms (e.g., OpenLCA), real-time material libraries (e.g., Matmatch, Granta MI), and compliance databases (e.g., EU FCM Positive List). Functionally, the interface should provide real-time validation of circularity metrics, simulate material degradation under expected use conditions, and visualize compliance risks through accessible dashboards.

The envisioned new circular P Configurator would be designed to integrate some interrelated features proposed in the following.

(a) Future for user engagement with a 3D visualization module that reflects real-time configuration changes, such as pouch type, closure system, or material choice. This feature builds directly on upgrading P current configurator, which already enables high- resolution previews of packaging formats. However, in the proposed circular configurator, the visualization would be dynamically linked to environmental metadata, such as recyclability indicators and carbon footprint metrics. This approach addresses a key limitation in current P configurator, which rarely incorporate material references into visual engaging representation.
(b) To support EoL decision-making, the next P configurator would include a strategic selector that evaluates the four EoL alternatives: reuse, mechanical recycling, chemical recycling, and organic recycling. Based on the materials selected, contamination risks, and local infrastructural constraints each option is algorithmically assessed against user-defined priorities, including regulatory compliance (e.g., EU PPWR), supply chain conditions, and intended market geography. This allows the next P configurator to simulate alternative scenarios and recommend design configurations that maximize the compatibility between the final configuration and the EoL strategy preferred. Materials such as polyethylene (PE), used widely by Packstyle in its mono-material recyclable films, are well- suited for mechanical recycling. In contrast, multilayer composite structures, while offering superior barrier properties, may require more advanced processing such as chemical depolymerization or solvolysis [14].
(c) Another core future would be the integration of traceability logic, operationalized through a digital passport that records component origin, recyclability classification, batch data, and additive presence. This feature directly supports regulatory goals under the European Green Deal and Digital Product Passport (DPP). By assigning a persistent digital identifier to each configuration, the configurator ensures that packaging complies with traceability mandates and facilitates reverse logistics. In this respect, the proposed system aligns with recent industry efforts to harmonize digital and physical product identities [35].
(d) Furthermore, a future that includes a modularity and disassembly module that enables users to simulate separability and detachment logic based on the selected closures, materials, and sealing methods. For instance, the inclusion of degassing valves or spouts which are options currently available in P catalog, could trigger a disassembly analysis that evaluates recyclability trade-offs, energy input for separation, and potential contamination vectors. The integration of features that support this decision-making possibility would be crucial for generating realistic circular products designed-for-disassembly.

Another feature would be a real time performance dashboard that provides real-time feedback through weighted indicators derived from the MCDA, allowing users to observe how different configurations perform across multiple sustainability dimensions. Rather than offering binary "valid/invalid" judgments, the interface could present clear trade-off visualizations that reflect system-level interactions among material properties, environmental impact, and operational feasibility. This design approach fosters user learning and internalization of CE logic, in line with recent findings on configurator-assisted behavior change.

The proposed new P Circular Configurator embodies a shift from conventional product customization to lifecycle-oriented design by embedding criteria such as modularity, traceability, and material knowledge which are identified in this study by packaging experts as core enablers of CE- aligned packaging. The proposed conceptualization of the configuration system extends the functional features of existing digital packaging tools and establishes a blueprint for how new digital product configurators can become strategic enablers of circularity in the packaging industry.

From a user point of view the configurator could implement a 3d products visualization while providing real time feedback on sustainable dimensions and circular pattern of the configuration. The proposed new P Circular Configurator, aims at evolving the current version from a passive interface into an active sustainability orchestrator that aligns packaging design processes with the Eco-design circular principle, the operational demands and the regulatory requirements in the packaging sector. As derived from expert-driven MCDA, next user interface of circular configurators should integrate four core capabilities such as (i) dynamic modularity: enabling flexible design variants that facilitate reuse and effortless disassembly; (ii) material traceability: ensuring each component is tagged with provenance, compliance, and recyclability metadata; (iii) embedded material data: incorporating polymer properties, contamination resistance, and process compatibility; (iv) strategy-adaptive logic: enabling prioritization of EOL pathways tuned to regulatory and contextual variables (Figure 1).

Figure 1: Simulation of new P Circular Configurator

source: our elaboration

6. Conclusion

The present study outlines a conceptual extension for packaging configuration systems into a next-generation digital product configurator designed specifically for circular economy compliance. Preliminary results from the present study multistep research design which includes a MCDA and AHP- evaluations performed by industry expert, the study provides preliminary result in researching on: (a) which sustainability criteria are considered most relevant by packaging industry when evaluating EOL strategies for packaging i.e. modularity, traceability, and materials knowledge results as critical enablers of sustainable packaging design. (b) Moves an initial step on exploring how do different EOL strategy (i.e., reuse, mechanical recycling, chemical recycling, organic recycling) are preferred by packaging industry experts which result to be chemical recycling however findings pointed out the importance of a multi-dimensional view of circularity where no single EOL strategy is inherently superior. Rather, the configurator must operate as a decision-support system capable of matching design choices to context-sensitive sustainability parameters. As well as exploring on (c) potential features to be implemented on a next-generation product configurator to support eco- design packaging. Furthermore, the preliminary results underscore that the choice of EOL strategies must be dynamically aligned with design features, environmental constraints, and user priorities. There are no single optimal solutions, only context-sensitive configurations capable of maximizing circular value retention. Even in its exploratory stage the present study reveals the role of product configurators as critical enablers of circular packaging systems that could support each stage of the packaging life cycle design, manufacturing, distribution, collection, and recovery. Future research should validate this framework through prototype development and field trials in actual packaging design workflows.

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Declaration on Generative AI

The Authors used Gemini to improve language proof. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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